

Turmoil in Orion: The Nearest Massive Protostar

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Abstract. I discuss different theories of massive star formation: formation from massive cores, competitive Bondi-Hoyle accretion, and protostellar collisions. I summarize basic features of the Turbulent Core Model (TCM). I then introduce the Orion Kleinmann-Low (KL) region, embedded in the Orion Nebula Cluster (ONC) and one of the nearest regions of massive star formation. The KL region contains three principal radio sources, known as “ I ”, “ n ” and “BN”. BN is known to be a runaway star, almost certainly set in motion by dynamical ejection within the ONC from a multiple system of massive stars, that would leave behind a recoiling, hard, massive, probably eccentric binary. I review the debate about whether this binary is Θ^1C , the most massive star in the ONC, or source I , and argue that it is most likely to be Θ^1C , since this is now known to be a recoiling, hard, massive, eccentric binary, with properties that satisfy the energy and momentum constraints implied by BN’s motion. Source n is a relatively low-mass protostar with extended radio emission suggestive of a bipolar outflow. Source I , located near the center of the main gas concentration in the region, the Orion Hot Core, is the likely location of a massive protostar that is powering the KL region, and I discuss how its basic properties are consistent with predictions from the TCM. In this scenario, the radio emission from source I is the base of a bipolar outflow that is ionized by the massive protostar and should be elongated along the axis of the outflow.

1. Introduction and Definitions

Understanding the formation of massive stars is an important problem for many areas of astrophysics including high redshift Population III star formation, galaxy formation and evolution, galactic center environments and supermassive black hole formation, star and star cluster formation, and planet formation around stars in clusters, which may be relevant to our own solar system. The problem is challenging because of the wide range of spatial and temporal scales, the complicated interplay of gravity, thermal pressure, magnetic fields, radiation and “turbulent” (i.e. nonthermal) motions, including bipolar outflows from surrounding stars, and the uncertain initial conditions, caused by high obscuration to the typically distant and crowded regions where massive stars form. Thus progress requires close testing of theoretical models against detailed observational data, such as is available for the nearest massive star-forming regions.

I adopt the following definitions (see also McKee & Tan 2003; Beuther et al. 2007): a *protostar* is a star (i.e. a near-equilibrium gaseous configuration in which gravity is balanced by thermal and radiation pressure and possibly rotation) accreting matter so that its mass, m_* , has not yet reached its maximum value, m_{*f} , that it is born with; a *massive protostar* (MP) or star has a mass \geq

$8M_{\odot}$; a *pre-(massive-)stellar core* is the self-gravitating (negative total energy), topologically-connected, matter surrounding the location where the (eventually massive) protostar first forms (at time $t = 0$); at later times when the protostar and rotationally-supported disk have formed, this system is a *(massive-)star-forming core*, which includes the mass of the protostar and disk (mass may join or leave the core during the growth of the protostar); in principle the evolution of the pre-stellar core at earlier times ($t < 0$) could be followed, defining its center to be at the minimum of the gravitational potential; a *star-forming clump* or *protocluster* is the system made up of a forming cluster of stars and the self-gravitating gas surrounding them. The minimum number of stars, which may be protostars, to define a cluster, $\mathcal{N}_{*,\min}$, can be debated: I suggest $\mathcal{N}_{*,\min} = 10 \gg 1$. For clumps, self-gravity should first be assessed for all the mass in the minimum convex volume that includes the \mathcal{N}_{*} stars, then surrounding stars and gas (including effects of external pressure) can be assessed to see if they are bound to, and therefore a part of, this structure.

Note, since the mass of a protostar when it first forms is expected to be very small ($\ll M_{\odot}$), massive protostars must have gone through a stage when they had low and intermediate masses. Beuther et al. (2007) refer to these as “Low to Intermediate Mass Protostars destined to become Massive Protostars” and here we suggest the abbreviation LIMP-MP, so the expected evolutionary sequence if massive star formation is a scaled-up version of low-mass star formation is Pre-Massive-Stellar Core \rightarrow Massive-Star-Forming Core containing LIMP-MP \rightarrow Massive-Star-Forming Core containing MP \rightarrow Massive Star. Much of the theoretical debate in the field centers on whether the pre-massive-stellar core is itself *massive* (i.e. with mass comparable to or larger than m_{*f}), whether the massive-star-forming core containing the LIMP-MP is *massive*, and whether there is a stage where the mass of the massive-star-forming core containing the MP is gas dominated. The alternative is that the core has a small mass when the protostar first forms and then accumulates the bulk of its mass during the star-forming stage while maintaining a relatively small gas mass fraction.

Star-forming clumps, which are typically supersonically turbulent, form new cores and protostars by “gravitational fragmentation” (but note that the material in the new cores will still be part of the clump, so the clump itself has not strictly speaking fragmented). New cores and protostars may also form inside existing star-forming cores. I distinguish “disk fragmentation” from “turbulent fragmentation”. In disk fragmentation, which only occurs inside star-forming cores, the new core (and protostar) is in a low eccentricity orbit about the original protostar, i.e. is gravitationally bound to it with infall mostly resisted by rotational support, and is likely to have its boundaries set by tidal forces from the original protostar. The original star-forming core maintains its identity, but now with a binary and circumbinary disk at its center. Turbulent fragmentation (e.g. Padoan & Nordlund 2002) can occur both inside and outside of star-forming cores. If it takes place inside a star-forming core, the new core will be bound to the previous core (it is part of it), but will not have its infall supported significantly by rotation. One expects that the enclosed mass for the position of the new core inside the old core will be dominated by the protostar in the case of disk fragmentation and (non-stellar) gas in the case of turbulent fragmentation, but these are not discrete categories.

If a star-forming core undergoes turbulent fragmentation, it is possible to view it as forming a sub-cluster within the main protocluster. This could be a major difference from the isolated mode of star formation that forms single stars (or binaries or higher multiples via disk fragmentation). Nevertheless the system can approximate that of isolated star formation from cores if a significant fraction, say $\geq 1/2$, of the *stellar* mass produced in the core is in a single star (or binary or higher multiple formed by disk fragmentation). In this situation there is still, approximately, a one-to-one correspondence of the core with the final principal star. Thus, another important discriminator between star formation models is the relative importance of turbulent fragmentation that occurs in gas that is already part of a star-forming core compared to gas that is part of the clump, but not yet associated with any particular protostar. It should be noted that since massive stars are rare (they contain a small fraction of the total young stellar mass), pre-massive-stellar cores are also rare: they require relatively special conditions to form.

Pre-stellar cores may form in a clump that is already rich in (proto)stars so that, especially for large, massive cores, some stars are embedded in the core volume. The orbits of these stars in the clump may be such that they are not bound to the new core, so that their mass is not formally part of the core by the above definitions, even though their mass played some typically minor role in defining its potential. As these stars orbit through and out of the core they may accrete some mass by Bondi-Hoyle accretion, with gas streamlines typically being intercepted by a pre-existing remnant disk from an earlier accretion phase. This Bondi-Hoyle accretion of the core gas is a continuation of Bondi-Hoyle accretion of clump gas that these protostars would have been experiencing prior to the formation of the core. Note that Bondi-Hoyle accretion involves accretion of gas that is initially not bound to the protostar (strictly speaking not bound to the star-forming core, which is composed mostly of the protostar, together with a remnant accretion disk). The mass affecting the gravitational cross-section here is dominated by the protostar. This is to be contrasted with accretion of gas to cores in which the gas mass fraction of the core is still significant and the gas distribution still extended. This latter case is less likely to be affected by protostellar feedback.

What if a pre-existing star is bound to the new core? Most stars in these environments will still have at least some remnant accretion disk and so will be protostars and thus would have had remnant cores of their own. This situation can be viewed in a number of ways. From the point of view of a new pre-massive-stellar core, it is just about to form with its new central, defining protostar (that later will become a massive star), but finds itself infested with older, pre-existing stars that may steal some of the massive core gas. From the point of view of the pre-existing protostars, they will likely see their boundaries grow, and maybe merge, as the massive core forms or grows around them, but their boundaries would not include the new LIMP-MP¹. They would likely experience enhanced accretion, possibly contributing significantly to their final mass.

¹A pre-massive-stellar core could in principle form inside a star-forming core by fragmentation, but then would be expected to have a low mass and to not typically contain pre-existing stars.

Given these possibilities, one basic question to answer is “how do massive protostars typically build up their mass?” The turbulent core model (McKee & Tan 2002, 2003) posits that massive stars form from massive, gas-dominated, relatively-near-equilibrium cores, that form by turbulent fragmentation from the magnetized clump medium or by pre-stellar-core agglomeration processes, have some significant fraction of their support from turbulent motions and that during their collapse channel a large fraction of the star-forming gas via a central disk into just one star (or a few stars formed by disk fragmentation).

An alternative possibility is competitive Bondi-Hoyle accretion without involving massive gas dominated cores around the massive protostar (Bonnell et al. 2001; Schmeja & Klessen 2004; Bonnell, Vine, & Bate 2004; Bonnell & Bate 2006). The gas in the core is a relatively small fraction of the massive protostellar mass, but is continuously being replenished by efficient accretion of gas that was previously not bound to the protostar. In these numerical models, this gas is typically being funneled to the center of a star-forming clump that is undergoing global collapse. For some of the massive stars formed in these models – those whose protostellar seeds are amongst the first to form in the cluster – their formation can be described as involving a massive gas core, but one which subsequently undergoes efficient turbulent fragmentation to put most of its mass into a cluster of low-mass stars. In neither of these descriptions is there a close correspondence between massive core mass and resulting massive star mass. Since these simulations only include thermal pressure and no magnetic pressure, it is not surprising that they do not see massive near-equilibrium cores, with masses much greater than the thermal Jeans mass, which is $< M_{\odot}$ in typical massive star-forming regions.

A third possibility, requiring extremely high stellar densities, is the growth of massive protostars by stellar mergers (Bonnell et al. 1998), which is effectively a merger of star-forming cores, followed by the merger of the protostars. Bally & Zinnecker (2005) invoked this mechanism to explain the “explosive” nature of the outflow from the Orion KL region (Allen & Burton 1993), although we shall see that another more likely possibility is the tidally-enhanced accretion and accretion-powered outflow from close passage of a fast-moving star (BN) with a massive protostar and accretion disk (source *I*) (Tan 2004).

2. The Turbulent Core Model

McKee & Tan (2002; 2003, hereafter MT03) modeled massive star formation by assuming an initial condition that is a marginally unstable, massive, turbulent core in approximate pressure equilibrium with the surrounding protocluster medium, i.e. the star-forming clump. This clump was also assumed to be in approximate hydrostatic equilibrium so that its mean internal pressure is $P \sim G\Sigma^2$, where $\Sigma = M/(\pi R^2)$ is the mean mass surface density with typical observed values $\sim 1 \text{ g cm}^{-2}$. This pressure sets the overall density normalization of each core and thus its collapse time and accretion rate. The core density structure adopted by MT03 is $\rho \propto r^{-k_{\rho}}$, with $k_{\rho} = 1.5$ set from observations. This choice affects the evolution of the accretion rate: $k_{\rho} < 2$ implies accretion rates accelerate. However, this is a secondary effect compared to the overall normalization of the accretion rate that is set by the core’s external pressure.

Since much of the pressure support in the core is nonthermal with significant contributions from turbulent motions, one does not expect a smooth density distribution in the collapsing core, and the accretion rate can show large variations about the mean. Also the assumption that the core is collapsing in isolation is of course approximate: MT03 estimate that during the collapse the core interacts with a mass of surrounding clump gas similar to its initial mass, although not all of this will become bound to the core. The mass spectrum of cores may be shaped by core agglomeration and disruption processes. The former will be more efficient in the dense centers of clumps, perhaps leading to more frequent massive core and massive star formation in these regions.

Predictions of the TCM are the properties of the cores and accretion disks of massive protostars. The initial core size is $R_{\text{core}} \simeq 0.06(M_{60})^{1/2}\Sigma^{-1/2}$ pc, where $M_{60} = M_{\text{core}}/60 M_{\odot}$. Note an allowance has been made for massive cores tending to be near the centers of clumps, where pressures are about twice the mean (MT03). These cores have relatively small cross-sections for close interactions with other stars. The accretion rate to the star, via a disk, is $\dot{m}_* = 4.6 \times 10^{-4} f_*^{1/2} M_{60}^{3/4} \Sigma^{3/4} M_{\odot} \text{ yr}^{-1}$, where f_* is the ratio of m_* to the final stellar mass and a 50% formation efficiency due to protostellar outflows is assumed, so $m_{*f} = 0.5M_{\text{core}}$. The collapse time, $1.3 \times 10^5 M_{60}^{1/4} \Sigma^{-3/4}$ yr, is short and quite insensitive to m_{*f} , allowing coeval stochastic high and low-mass star formation in a cluster, that might take $\gtrsim 1$ Myr to build up. The disk size is $R_{\text{disk}} = 1200(\beta/0.02)(f_* M_{60})^{1/2} \Sigma^{-1/2} \text{ AU}$, where β is the initial ratio of rotational to gravitational energy of the core, and the normalization is taken from typical low-mass cores (Goodman et al. 1993), although there is quite a large dispersion about this value.

These estimates of the accretion rate allow quantitative models of the protostellar evolution, allowing prediction of the stellar radius $r_*(m_*)$, luminosity $L_*(m_*)$, H-ionizing luminosity $S_*(m_*)$, disk structure and outflow intensity, which can then be compared to observed systems (see Figure 1 of Tan 2003). For example, a $20M_{\odot}$ protostar accreting from an originally $60M_{\odot}$ core near the center of a $\Sigma = 1 \text{ g cm}^{-2}$ clump would have $L_* \simeq 10^5 L_{\odot}$ and $S_* \sim 10^{48} \text{ photons s}^{-1}$. The protostellar outflow should have injected $\sim 5000 M_{\odot} \text{ km s}^{-1}$ of momentum into the surrounding gas, enough to eject a substantial fraction of the original core material in directions above and below the accretion disk. The outflow can also confine the ionizing luminosity in equatorial directions, creating an outflow-confined hypercompact HII region (Tan & McKee 2003).

3. The Orion KL Region

The closest massive protostar is thought to be radio source *I* (Menten & Reid 1995) in the Orion Kleinmann-Low (KL) region, 414 ± 7 pc away (Menten et al. 2007). This region is near the center of the Orion Nebula Cluster (ONC), marked by the Trapezium OB stars. Also nearby is the Becklin-Neugebauer (BN) object, known to have a high proper motion, equivalent to about 40 km s^{-1} in the plane of the sky (Plambeck et al. 1995; Tan 2004; Gómez et al. 2005), and source *n*, a relatively low-luminosity, low-mass protostar (Gezari, Backman, & Werner 1998).

3.1. The BN Object: A Runaway Star Ejected from Θ^1C

BN's luminosity is $\sim 2500 - 10^4 L_\odot$ (Gezari et al. 1998), corresponding to a zero age main sequence B3-B4 (8-12 M_\odot) star. It is highly likely that BN originated in the ONC. Since the cluster is too young for binary supernova ejections, the most plausible model for BN's motion is dynamical ejection from an unstable triple or higher order system. This can often occur when a hard binary interacts with another star (Hut & Bahcall 1983). Typically the least massive star is ejected at about the escape speed from the remaining binary at the orbit of the secondary, which is often left eccentric.

I have proposed BN was ejected from an interaction with the Θ^1C system (Tan 2004) because: (1) Θ^1C lies along BN's past trajectory; (2) Θ^1C has a proper motion direction opposite to BN's (van Altena et al. 1988); (3) Θ^1C has a proper motion amplitude that would predict BN's mass is $6.4 \pm 3 M_\odot$, in agreement with the estimate from its luminosity; (4) Θ^1C has a relatively massive ($\gtrsim 6 M_\odot$) secondary companion (Schertl et al. 2003) (now known to be $15.5 M_\odot$, Kraus et al. 2007); (5) the orbit of the Θ^1C secondary is now known to be highly eccentric ($e = 0.91$, Kraus et al. 2007; however, this is disputed by Patience et al. 2008); (6) the semi-major axis of the Θ^1C binary (total mass $\simeq 50 M_\odot$) is about 17AU and the escape speed from this distance is 70 km s^{-1} , high enough to explain BN's speed (the binding energy of the binary is now known to be 2.6×10^{47} ergs compared to BN's kinetic energy of $\simeq 1.6 \times 10^{47}$ ergs). To have all of the above occur by chance is highly improbable. Furthermore, no other revealed, massive ONC stars have any of the correct proper motion or binary properties.

Gómez et al. (2005) and Rodriguez et al. (2005) proposed that BN was ejected from an interaction with source *I* and source *n* from a location about $4''$ to the NW of source *I*'s current position. This is based on the apparent radio proper motions of *I* and *n*. However, both these radio sources are elongated along directions parallel to the claimed proper motion vectors, increasing the uncertainties in the derived motions. The dense gas and dust that now appears in the vicinity of source *I* on scales $\gtrsim 100 \text{ AU}$ (Blake et al. 1996; Wright et al. 1996; Beuther et al. 2006) could not have been retained by the star if it had been subject to such an ejection event. I expect that source *I* has a much smaller proper motion relative to the ONC than has been claimed, and that it is forming from the surrounding gas core in which it is now embedded.

3.2. Source I: Core, Disk, Protostar and Outflow

Wright et al. (1992) mapped a core of dense gas in the KL region in emission at $450 \mu\text{m}$ and 3.5 mm : the center of this source is often referred to as the Orion Hot Core. This core is centered close ($\lesssim 1''$) to the position of source *I* and has a scale of about 0.05 pc ($25''$) across its short axis in the SE to NW direction. The core is elongated along the NE to SW axis, and indeed it likely part of a larger-scale filamentary feature in these directions. The scale of the core is similar to that expected for an initially massive $\sim 60 M_\odot$ core in near equilibrium with a $\Sigma = 1 \text{ g cm}^{-2}$ clump (see §2). Wright et al. (1992) estimate a current core gas mass of about $17 - 38 M_\odot$. This core was also probed by its extinction in the $9.8 \mu\text{m}$ silicate feature by Gezari et al. (1998), with the extinction peaking close to source *I*. The polarization vectors of near to mid IR

emission suggest that a single source is responsible for much of the luminosity from the core (Werner, Capps, & Dinerstein 1983).

Wright et al. (1995) interpreted SiO ($v=0$; $J=2-1$) maser emission that is centered about source *I* as indicating the presence of a $r \sim 1000$ AU accretion disk (perhaps interacting with an outflow so that motions are not precisely Keplerian). This scale is similar to that estimated from collapse of a core with $\beta = 0.02$ (§2). The velocity of maser spots from different sides of the disk suggest a central mass of about $20 M_{\odot}$. There is apparent elongation along the SW to NE axis because of the inclination of the disk with respect to our line of sight. The disk alignment is perpendicular to the large scale molecular outflow to the NW and SE (Chernin & Wright 1996). The apparent “explosive” appearance of the inner part of this outflow (Allen & Burton 1993) could be due to tidally-enhanced accretion and accretion powered-outflow caused by the close passage of BN with source *I* about 500 years ago (Tan 2004). It should be noted that the outflow extends beyond the region that is usually considered to be “explosive” (e.g. Henney et al. 2007), as would be expected in this scenario where the protostar is $\sim 10^5$ yr old.

To derive the properties of the protostar, we can consider the bolometric luminosity coming from the KL core, $\sim 5 \times 10^4 L_{\odot}$ (Kaufman et al. 1998; Gezari et al. 1998), with an uncertainty at about the factor of 2 level. Comparing to the protostellar evolution models of McKee & Tan (2003), one possible set of parameters for the protostar is: $m_* = 18 M_{\odot}$, $\dot{m}_* = 3.6 \times 10^{-4} : M_{\odot} \text{ yr}^{-1}$ and $S_* \sim 4 \times 10^{47} \text{ s}^{-1}$ (Tan 2003).

The ionizing photons will interact primarily with the outflow gas as it is magneto-centrifugally-launched up from the accretion disk, creating an “outflow-confined HII region” (Tan & McKee 2003). These HII regions are unconfined in polar directions along the disk/outflow rotation axis, and if the ionizing flux is strong enough, can become unconfined in near-equatorial directions also. However, their emission measure will always be strongly peaked around the protostar because of the approximately r^{-2} density profile in the outflow. Tan & McKee (2003) showed this model fits the radio spectrum of source *I* very well, and naturally explains the observed elongation of the radio source along the NW-SE axis (Reid et al. 2007), i.e. parallel to that of the larger scale outflow (Chernin & Wright 1996). The position angle of elongation aligns well with a particular Herbig-Haro object to the NW (Taylor et al. 1986) requiring flow velocities $\sim 1000 \text{ km s}^{-1}$, which is about the escape speed and expected maximum outflow velocity from a $20 M_{\odot}$ protostar.

SiO ($v=1$ & 2) masers have been observed surrounding the radio source on scales of several tens of AU (Greenhill et al. 2004; Greenhill et al., these proceedings). The densities and temperatures of the gas in the outflow-confined HII region model are appropriate for the excitation of these masers. However, the maser velocities are rather low ($\sim 10 - 20 \text{ km s}^{-1}$), although there are observational biases against detecting relative velocities $\gtrsim 50 \text{ km s}^{-1}$ (Greenhill & Matthews, priv. comm.). A velocity gradient is seen along the elongated direction of source *I*. Greenhill et al. (2004) used this to argue that the disk is in fact orientated along this axis, perpendicular to the previously described disk model. However, there is little evidence for a large outflow or outflow cavity in the direction expected for this orientation (rather the opposite: a large amount

of dense gas and extinction; Gezari et al. 1998) and a new source would be needed for the powerful NW-SE outflow. Possibilities to reconcile the observed SiO ($v=1$ & 2) maser motions with the outflow-confined HII region model include: (1) the maser features may correspond to patterns of temperature and density variation rather than actual gas motion; (2) very particular orientations of protostar, gas and our line of sight may be needed for maser amplification so that the full velocity field is not sampled; (3) SiO emission may be limited inside the dust destruction front (very few maser spots are seen with projected distances < 10 AU from the center of source *I*) and so the observed spots may trace the kinematics of gas launched from regions beyond the dust destruction front, where the escape speeds are only about a few tens of km s^{-1} .

4. Conclusions

It is remarkable that, given its astrophysical importance, massive star formation remains so poorly understood. Theories that involve basic differences in the accretion mechanism are actively debated. After defining the terminology and physical properties expected of cores forming together in a star-forming clump, we see that the theoretical differences boil down to whether massive star formation proceeds from massive gravitationally bound gas cores or from competitive accretion to protostellar seeds that are already well-formed before much of their gas is accumulated - i.e. in this latter case the local core potential is mostly determined by the stellar mass rather than the gas mass. We favor the theory of massive star formation from massive gas cores, and suspect numerical models will support this view once they include the physics of magnetic fields (that can help support massive cores) and feedback from protostellar outflows and radiation pressure (that inhibit Bondi-Hoyle accretion and small scale fragmentation near massive protostars - Krumholz 2006).

However, even in the context of models of formation from massive gas cores, understanding what is going on in even the nearest massive protostar and core remains challenging. The Orion KL region is crowded with young stars, and close dynamical interactions definitely occur between them, such as must have accelerated the BN object. I have argued Θ^1C is responsible for this event, because it satisfies all the required properties expected of the recoiling, eccentric, hard, massive binary system that must be left behind. As proper motion measurements improve, this issue should be resolved definitively. Source *I* is likely to be an actively accreting massive protostar, that was perturbed by BN's close passage. However, even the orientation of the disk/outflow axis of this system is debated from two orthogonal possibilities. Outflow-confined HII regions are a prediction of massive star formation models that are scaled-up versions of low-mass star formation models. The radio spectrum and morphology of source *I* can be explained by this type of model, but the kinematics of the excited SiO maser spots on 20-100 AU scales remain mysterious.

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